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Marianne G. Tarczal

RESPONSE

This Response is in reply to the Office Action mailed March 28, 2002 in the subject application. In response to the Office Action, please amend the above-identified application as follows.

AMENDMENT C

Please amend the application as follows:

In the specification:

Please amend the paragraph beginning on page 1, line 5 and ending on page 1, line 6 as follows:

This invention relates to the field of high voltage modulators and, more particularly, to solid state modulators for high voltage systems.

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02 FC:203 234.00 OP
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Please amend the paragraph beginning on page 3, line 12 and ending on page 3, line 17 as follows:

For some applications, however, the apparatus described in the '610 patent may be physically large and expensive to manufacture. For example, to switch 120 kV, up to 160 series connected IGBTs may be required, which presents size and configuration challenges. In addition, so that no single IGBT sees harmful or destructive voltages, the load must be shared equally among the IGBT devices. Therefore, the gate drives for the IGBT devices must be precisely synchronized.

Please amend the paragraph beginning on page 3, line 18 and ending on page 4, line 2 as follows:

Thus, an object of the present invention is to incorporate serially connected low voltage switches having load sharing features in a compact, transformer coupled gate switch. By floating each IGBT and its respective gate drive circuitry with respect to ground, by ensuring that all power and control connections to the IGBT and its gate drive are isolated, and voltage limiting means are provided, no single IGBT will experience a voltage greater than its design limit. In addition, the IGBT devices can be highly synchronized and, therefore, can switch substantially simultaneously.

Please amend the paragraph beginning on page 4, line ⁴12 and ending on page 4, line ¹²11 as follows:

Thus, the present invention features a modulator that comprises one or more transformers and a plurality of switches. The transformers comprise a primary and a

plurality of secondary windings. Each secondary winding has an output terminal pair. Each of the plurality of switches is associated with a respective secondary winding and has an output-high terminal and an output-low terminal and a control terminal pair. The control terminal pair of each switch is in electrical communication with a respective output terminal pair of the plurality of secondary windings. When an input signal is applied to the primary of the transformer, a signal is induced in the secondary such that the plurality of switches, which are each coupled to a respective secondary winding, are switched substantially simultaneously.

Please amend the paragraph beginning on page 4, line ¹³~~12~~ and ending on page 4, line ²¹~~20~~ as follows:

In one embodiment, the modulator further comprises a stack of switch modules sharing the same primary as shown in Figs. 5 and 6. In other embodiments, the modulator further comprises at least one voltage limiter, such as a Zener diode or snubbing circuit, and in one embodiment the at least one voltage limiter is connected in parallel with the output terminal pair of at least one of the plurality of switches. In another embodiment, the plurality of switches are connected in series or in parallel to better match the properties of the load. In further embodiments, at least one of the plurality of switches comprises a transistor, such as an insulated gate bipolar transistor (IGBT), an avalanche-rated field effect transistor (FET), or a power metal oxide FET (MOSFET).

Please amend the paragraph beginning on page ⁵~~4~~, line ¹~~21~~ and ending on page 5,

line ¹³1 as follows:

The present invention also features a modulator comprising a transformer, a plurality of retriggerable drive circuits, and a plurality of switches as shown in Figs. 7 and 8. The transformer includes a primary and a plurality of secondary windings. Each of the plurality of retriggerable drive circuits has an output terminal pair and is electrically connected to a respective one of the plurality of secondary windings. Each of the plurality of switches is associated with a respective retriggerable drive circuit and has an output terminal pair and a control terminal pair. The control terminal pair of each switch is in electrical communication with a respective output terminal pair of the retriggerable drive circuit with which it is associated. In one embodiment of the invention, the modulator comprises a stack of switch modules sharing the primary of the transformers. In operation, when an input signal is applied to the primary of the transformers, each of the plurality of switches is switched substantially simultaneously and remains substantially on until a second signal is applied to the primary of the transformer to turn the switches off.

Please amend the paragraph beginning on page 5, line ¹⁴2 and ending on page 5, line ²20 as follows:

The present invention also features a method of switching a signal. An input signal is applied to the primary of a transformer. In response to this input signal, a voltage is induced in a plurality of secondary windings of the transformer. This induced voltage switches, substantially simultaneously, each of a plurality of switches that are electrically controlled by a respective one of the plurality of secondary windings. In one

embodiment of the invention, each of the plurality of switches is maintained in a substantially conducting state after termination of the input trigger signal. In another embodiment, a gate reset input trigger pulse signal is applied to the single primary winding of the transformer.

Please amend the paragraph beginning on page ⁶~~5~~, line ¹~~21~~ and ending on page 6, line ⁵~~3~~ as follows:

The present invention also features a modulator that may be used as a very large, very fast series switch, or circuit breaker that enables high power systems to be turned on and off in a rapid, repeatable, and controllable way. When the modulator is used as a switch, power can be substantially removed from the load when the switch is 'off', that is open.

Please amend the paragraph beginning on page 6, line ¹⁸~~18~~ and ending on page 6, line ¹⁹~~17~~ as follows:

Fig. 5 is a three dimensional diagram of one embodiment of the switch modules of the present invention.

Please amend the paragraph beginning on page ⁷~~6~~, line ¹~~18~~ and ending on page 6, line ²²~~19~~ as follows:

Fig. 6 is a simplified schematic of a modulator that includes stacked switch modules in accordance with the invention.

Please amend the paragraph beginning on page 7, line ~~8~~⁸ and ending on page 7, line ~~18~~¹⁷ as follows:

Modulators are electronic devices used to precisely regulate the delivery of high voltage, high current electrical pulses. A modulator can act as a simple series switch between a high power supply and its load (such as a klystron). Ideally, modulators have infinite voltage holdoff, infinite off-resistance, zero on-resistance, and full immunity to transients and voltage reversals. Modulators are critical components of electronic systems used for numerous applications such as radar systems, particle accelerators, medical diagnostics and treatment equipment, and manufacturing equipment, such as ion implantation for semiconductor fabrication. In addition, new processes for food sterilization, waste treatment, and pollution control are also being developed which require the use of high power modulators.

Please amend the paragraph beginning on page 8, line ~~4~~⁴ and ending on page 8, line ~~14~~¹⁴ as follows:

Achieving a nearly ideal pulse is critical to the performance of a number of pulsed power applications. An "ideal pulse" has instantaneous rise and fall time and a flat top, independent of load current and repetition rate. In ion implantation applications, for example, it is critical to minimize the voltage drop and pulse-to-pulse voltage variation to achieve uniform doping. This require very fast rise and fall times to minimize the energy provided at voltages other than the amplitude of the pulse. It also requires a very flat-top for the pulse, with no ripple or droop. In radar applications, the rise and fall times must be within the amplifiers' operating parameters. The flat top is very critical to parameters

such as phase noise. Generating pulses that most closely approach the ideal pulse waveform is, therefore, often a critical objective of high pulsed power system design.

Please amend the paragraph beginning on page 8, line ¹⁵~~12~~ and ending on page ⁹~~8~~, line ²~~20~~ as follows:

Historically, vacuum switch tubes or thyratrons, alone, or in combination with PFNs and pulse transformers, have been used to generate pulse waveforms. These conventional switches have non-ideal behavior, such as a large effective voltage drop, limited current capability and speed, high maintenance, and complex driving and protection circuitry. Nevertheless, they have dominated high-voltage switching until recently because no cost effective alternatives have been available. As future system requirements extend to higher voltage and power, however, the use of switch tubes becomes increasingly impractical due to the inherent voltage and current limits of these devices.

Please amend the paragraph beginning on page 9, line ⁹~~1~~ and ending on page 9, line ¹⁹~~15~~ as follows:

The present invention features a solid state modulator that can be used in systems that would otherwise require a switch tube, spark gap, or thyatron pulse forming network (PFN) modulator to switch high voltage and power. Fig. 1 illustrates a modulator 10 according to the present invention that is connected between a power source 21 and a load 14. The modulator 10 includes a transformer 16 connected to the control driver 12, and a plurality of switches 18 connected in series. The transformer 16 further includes a

primary winding 20 and a plurality of secondary windings 22. The primary winding 20 may be connected to ground potential while the plurality of secondary windings 22 may float at staggered high voltages. In one embodiment of the invention, the primary winding 20 further includes an input terminal pair and each secondary winding 22 further includes an output terminal pair.

Please amend the paragraph beginning on page 9, line ²⁰~~16~~ and ending on page ¹⁰~~9~~, line ⁵~~22~~ as follows:

In addition, although the primary winding 20 is illustrated in Fig. 1 as a single winding, in other embodiments of the invention, the primary winding 20 is a plurality of turns that achieve a predetermined turns ratio (i.e. 2:1 or 4:1). In another embodiment, the primary winding 20 may be a portion of a winding such as a half-turn of a winding. In another embodiment the primary winding 20 is a distributed primary winding. Distributing the winding can improve geometrical packing and reduce leakage inductance.

Please amend the paragraph beginning on page 10, line 1 and ending on page 10, line 9 as follows:

The transformer 16 can be formed using a toroidal core comprising a high permeability material such as ferrite. Using a toroid provides the advantage that the length and conformation of wire forming each secondary winding 22 will be essentially the same, so that the switches 18 will turn off and on at the same time. In another embodiment (as described in connection with Fig. 6), the modulator 10 includes one or

more switch modules stacked together, with the transformer 16 of each switch modules sharing the same primary winding 20. In one embodiment, the stacked modulator configuration comprises stacks of toroids forming the transformers 16 of the modulators. Closely stacking the toroids is advantageous because it helps to reduce leakage inductance and enables building modules of very high voltage.

Please amend the paragraph beginning on page 10, line 10 and ending on page 10, line 18 as follows:

Each switch 18 is associated with a respective secondary winding 22. In one embodiment (not shown), each switch is electrically coupled to a respective output terminal pair of the respective secondary winding 22. Each switch 18 includes a transistor, such as an insulated gate bipolar transistor (IGBT), an avalanche FET, or a power MOSFET. For example, a modulator 10 may include an arbitrary number of switches 18, such as IGBTs, connected in parallel and/or in series (which is explained further below). In one embodiment, the switches 18 include a combination of different types of switches, such as a combination of IGBTs and avalanche FETs. In one embodiment, each switch 18 includes an output voltage limiting means. In another embodiment, each switch 18 includes an input voltage limiting means and an output voltage limiting means, such as disclosed in the '610 patent.

Please amend the paragraph beginning on page 11, line 3 and ending on page 11, line 8 as follows:

In comparison, IGBTs have the high input impedance and high speed

characteristics of a MOSFET with the conductivity characteristics of a bipolar transistor. In addition, IGBTs can be turned on and turned off electronically, in contrast to thyristor switches conventionally used in some power modulators, which can only be turned on electronically. The fact that IGBT and MOSFET switches turn off electronically with low-power control pulses eliminates the need for PFNs in the modulator.

Please amend the paragraph beginning on page 11, line 9 and ending on page 11, line 12 as follows:

IGBT switches may be characterized by a low voltage drop in their on-state, for example about 2.5 Volts, so that in saturation the IGBT is essentially a Darlington pair configuration with a FET as the input stage and a bipolar power transistor for the output stage. The rise time of IGBTs is largely determined by the gate drive circuitry, as described below.

Please amend the paragraph beginning on page 11, line 17 and ending on page 12, line 6 as follows:

When the switches 18 are connected in series, as illustrated in Fig. 1, each individual series connected switch 18 operates with a floating ground reference. Consequently, all switches will perform identically and none should experience any voltage greater than its design limits regardless of the end of the series stack at which it is located. Each switch 18 and its gate drive circuitry (not shown) can “float” relative to ground, and all enabling and control connections to the switches 18 may be made inductively. Thus, in the embodiment illustrated in Fig. 1, a trigger can be applied at the

input 9 and enabling power 21 to be applied to the load via switches 18. In response to the control signal applied to the primary, a voltage is induced at each secondary 22 of the transformer at substantially the same time. Thus, switches 18 will be switched substantially simultaneously.

Please amend the paragraph beginning on page 12, line 7 and ending on page 12, line 18 as follows:

In one embodiment, the switch 18 is an IGBT, the FET inputs (i.e., the gate signals) are electrically coupled in parallel to the transformer 16 and the outputs of each switch 18 are connected in series with the load 14. The primary winding 20 of the transformer is at ground potential and the secondary windings 22 are floating at staggered high voltages. For a typical IGBT switch, the gate capacitance for each IGBT is approximately 5 nF. During operation, the entire modulator 10 acts as a high voltage switch, so that when an input signal is applied to control driver 12 and power 21 is applied, the switches 18 are switched substantially simultaneously. Because the switches are in series, very high voltages can be switched. For example, if switch 18 is a 1200V IGBT switch and three windings are used as shown in Fig. 1, the circuit of Fig. 1 can switch 3600V by switching 1200V across each switch 18. Additional switches can be added to switch even higher voltages.

Please amend the paragraph beginning on page 12, line 19 and ending on page 12, line 22 as follows:

In some embodiments of the invention, the modulator 10 can further include one

or more voltage limiting devices to protect the switches 18. Fig. 2 illustrates a modulator 10 that includes a plurality of output voltage limiting devices 24. Each output voltage limiting device 24 is connected in parallel with a respective switch 18.

Please amend the paragraph beginning on page 13, line 7 and ending on page 13, line 12 as follows:

In another embodiment, the switch 18 comprises an avalanche-rated FET that has a voltage limiting capability. Regardless of the type of voltage limiting technique used, if the voltage applied to the switch 18 is above a predetermined value, then the excess current induced by load 14 or source 21 will be conducted through the output voltage limiting device 24. The corresponding voltage drop across the voltage limiting device 24, however, will be substantially independent of the current conducted therethrough.

Please amend the paragraph beginning on page 13, line 13 and ending on page 13, line 20 as follows:

Fig. 3 illustrates a schematic diagram of one embodiment of the modulator 10, in accordance with the present invention. Eleven IGBT switches 72 are shown to be connected in series and are driven by parallel 1:1 windings. It should be understood, however, that the illustrations of this figure, including the windings on the transformer, are provided by way of example only. Numerous other configurations of windings can be used. For example, better geometrical packing of the windings can reduce transformer leakage. This can be accomplished by using a distributed primary winding, or by using additional windings (i.e., 2:1 or 4:1).

Please amend the paragraph beginning on page 13, line 21 and ending on page 14, line 4 as follows:

In addition, because leakage inductance affect the current induced in the primary, it may be advantageous to adjust the turns ratio for step-down operation with higher voltage primary drive. For example, a 4:2 step down can be used with a 35 Volt peak-to-peak drive on the transformer primary. In another example, the transformer 16 can be made from a ferrite toroid, and the ferrite toroid can be biased at the midpoint of the switches 18 to reduce the maximum voltage developed between the core of transformer 16 and the switches 18.

Please amend the paragraph beginning on page 14, line 5 and ending on page 14, line 9 as follows:

In another embodiment (not shown), the transformer 16 can have multiple primary windings in parallel to improve geometrical packing (and reduce leakage inductance). This technique helps to overcome induction limitations of the leakage inductance without adding capacitance to the circuit.

Please amend the paragraph beginning on page 14, line 10 and ending on page 14, line 17 as follows:

The series connection of switches illustrated in Figs. 1, 2, and 3 provide increased voltage handling capability. In contrast, Fig. 4 illustrates another embodiment of the invention wherein the switches 18 are connected in parallel, to provide increased current

handling capability. In this embodiment, a control signal, such as a trigger, is applied by control driver 12, and this signal is coupled substantially simultaneously to each switch 18, so that the switches 18 can substantially simultaneously switch current from the electrical power source 21. The ability to substantially simultaneously switch current from the power source increases the current handling capability of the modulator 10.

Please amend the paragraph beginning on page 14, line 18 and ending on page 15, line 2 as follows:

Fig. 5 is a three dimensional diagram representing of one embodiment of a switch module of the present invention. The switch module 50 includes a transformer 16 formed of a ferrite toroid core. As described above, using a toroid core is advantageous because the length and conformation of wire forming each secondary winding 22 can be substantially the same. This enables each switch 18 to turn off and on at substantially the same time. Switches 18 are positioned around the toroid core 16 and are connected to the secondary windings 22 as described above.

Please amend the paragraph beginning on page 15, line 3 and ending on page 15, line 6 as follows:

The switch module 50 can be surrounded by an epoxy casting 54, as illustrated in Fig. 5. Power and load terminals 56 may be positioned at the edges of the epoxy casting 54. The switch module 50 of Fig. 5 is particularly suitable for stacking multiple switch modules as described below in connection with Fig. 6. Heat exchangers 52 serve to remove from the modulators heat generated in the switches 18.

Please amend the paragraph beginning on page 15, line 7 and ending on page 15, line 13 as follows:

Fig. 6 is a simplified schematic of a modulator 10 that includes stacked switch modules 51 that share the same primary winding 20 in accordance with the invention. Each switch 18 may include input voltage limiting means and output voltage limiting means (both not shown). The ability to stack switch modules and use the same primary winding to substantially simultaneously switch all switches in each of the modulators is particularly advantageous. By stacking switch modules, one skilled in the art can scale the modulator power level to any desired levels of power and voltage and avoid limitations of the prior art.

Please amend the paragraph beginning on page 15, line 14 and ending on page 16, line 3 as follows:

Thus, in the configurations described above, the present invention provides a very fast high-voltage switch. There are several advantages of modulators of the present invention. For example, the modulators of the present invention can replace protective 'crowbars' in vacuum tube applications because the modulators can typically open and close in less than 0.5 μ S. If either instantaneous or average current through the switch rises above pre-set limits, the modulator simply opens, removing power from the load. The delay from sensing of an over-current condition, such as an arc, to the opening of the switch, can be kept well below 1 μ S. Another advantage is that the 'opening' of the series solid state switch does not shut down power supply operation, as with most

conventional crowbars. Furthermore, the modulators of the present invention may also be used as alternatives to conventional circuit breakers in power distribution systems.

Because these switches are both opening and closing switches, power can be substantially and “instantly” removed from the load when the switch is commanded to its off state.

Please amend the paragraph beginning on page 16, line 4 and ending on page 16, line 8 as follows:

When the modulator of the present invention is used as a pulse modulator, the opening and closing of the modulator is controlled by a command signal at low voltage that is applied to the primary of the transformer. The result is a stream of high power pulses into the load, each with rapid (sub-microsecond) rise and fall times, and extremely consistent pulse-to-pulse characteristics.

Please amend the paragraph beginning on page 16, line 9 and ending on page 16, line 16 as follows:

As described previously, consistent pulse-to-pulse characteristics and fast rise times are very desirable for many applications. Thus, because the switch design and construction can be identical in both a pulsed application and as a series switch, the modulator of the present invention can be used simultaneously as a pulse modulator and as a fast fault protection disconnect system. This can significantly simplify the overall design of systems that incorporate such modulators. Because solid state modulators do not use resonant circuits, each pulse can be arbitrarily sized. This allows complete pulse width and separation flexibility from 30 nS to DC.

Please amend the paragraph beginning on page 17, line 1 and ending on page 17, line 6 as follows:

The transformer 16 is configured as described previously in connection with Figs. 1 through 4. Each retriggerable drive circuit 28 is electrically connected with a respective one of the plurality of secondary windings. Each switch 18 has output-high and output-low terminals and a control terminal pair and is associated with a respective retriggerable drive circuit 18. The control terminal pair of each switch 18 is electrically connected with the output pair of the respective retriggerable drive circuit 28.

Please amend the paragraph beginning on page 17, line 7 and ending on page 17, line 12 as follows:

During operation, when a first control signal is applied to the primary of transformer 16 via the input 9, a voltage is induced in each secondary of the transformer 16. Then, each of the plurality of switches 18 is substantially simultaneously switched by the first signal applied to the primary and remains substantially on until a second signal is applied to the primary of the transformer 16. During this time, each switch 18 can switch the power from power supply 21.

Please amend the paragraph beginning on page 17, line 13 and ending on page 18, line 2 as follows:

Ideally, once a switch 18 is switched on, it is not necessary to hold it in the “on” position once switching is complete. Because the input of the switch looks like a

capacitor to the secondary of the transformer 18, large drive currents are only necessary to charge this capacitance quickly, but no drive current is necessary to sustain it. Thus, in theory, the primary pulse can be turned off, and the switch 18 will remain on (if the gate is isolated by a diode) until a negative pulse is provided. In practice, however, the transformer flux will reset, pulling the gate on the control input of the switch 18 negative by a small amount and shutting down the switch 18. In addition, the gate capacitance of the switch 18 is accompanied by a finite leakage, which will eventually increase the "on" state conduction losses and finally shut down the pulse. Both of these problems can be overcome by using the retriggerable drive circuit 28 of Figs. 7 and 8.

Please amend the paragraph beginning on page 18, line 3 and ending on page 18, line 11 as follows:

In operation, a gate pulse, such as a positive going pulse, passes transparently through the series FET and Zener diode of each of the retriggerable drive circuits 28, so each of the switches 18 will be switched on substantially simultaneously. When the gate pulse ends or the core of transformer 16 saturates however, the core reset voltage is insufficient to conduct through the series Zener (which has a blocking voltage of about 5V) of the retriggerable drive circuit 28. Therefore, the series FET of the retriggerable drive circuit 28 blocks the reverse bias during reset. In this manner, each switch 18 remains on either until a negative-going "end of pulse" trigger is sent through the primary, or until the gate charge leaks away. The gate leakage can be mitigated by simply retriggering a short on pulse to keep the switch on indefinitely.